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RESEARCH ARTICLE

Synthesis and X-ray crystal structures of selected ω-mercaptosulfones

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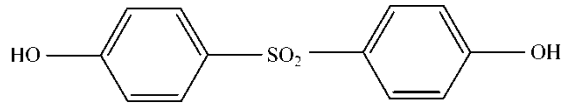
Three homologous ω-mercaptosulfones have been prepared and their crystal structures refined. When a single methylene (compound **3**) was interposed between the p-toluenesulfonyl and thiol moieties, neither intramolecular nor intermolecular H-bonding was observed in the crystals. When an ethylene segment (compound **4**) was interposed between the p-toluenesulfonyl and thiol moieties, one intermolecular H-bond per molecule was observed. When a propylene segment (compound **5**) was interposed between the p-toluenesulfonyl and thiol moieties, H-bonded molecular dimers were formed in the crystal structure.

Keywords: Mercaptosulfone; Synthesis; Crystallography; Disorder

1. Introduction

Some time ago, the authors reported a crystallographic study of the phenolic sulfone **1** [1]. The initial expectation was that intramolecular H-bonding between phenolic hydroxyl groups and sulfonyl oxygen atoms might lead to a novel self-assembly in the crystals. In the event, the phenolic sulfone **1** provided the first-known example of a homogeneous compound which forms a doubly-interwoven molecular carpet architecture in the solid state [1].



1

During an examination of a benzylic sulfide chlorinolysis, [2] the α-mercaptosulfone **2** was selected as a synthetic target. The successful synthesis of **2**, the first-known α-mercaptosulfone,

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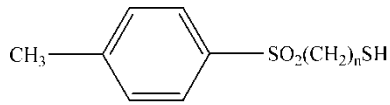
revealed that it is a metastable oil with a half-life of six days [3].

$CH_3SO_2CH_2SH$

2

Thereafter, the stable, crystalline α-mercaptosulfone **3** was prepared and its structure established chemically [4].

Consideration of the molecular structure of the α-mercaptosulfone **3** suggests that this molecule could exploit both intermolecular and intramolecular H-bonding in its crystals; these bonds are most likely between the mercapto hydrogen and an oxygen atom in the same or adjacent molecules. In part to investigate this possibility and how such bonding would affect the crystal packing, a crystallographic study of **3** and its structural relatives **4** and **5** was undertaken.



3 n = 1
4 n = 2
5 n = 3

Both of the α-mercaptosulfones **2** and **3** were prepared from appropriate α-sulfone disulfides. The author's interest in α-sulfone disulfides has included biological testing against phagocytosis of red blood cells [5], malaria [6], leukemia [7, 8], blood clots [9, 10] and fungi [4, 11–17]. Of the α-mercaptosulfones, only **3** has been screened, biologically, and it proved to be inactive against *A. niger* and *A. flavus*.

2. Experimental

2.1 *Synthesis*

2.1.1 General. Infrared spectra were recorded on a Thermo Nicolet 2000 spectrophotometer. ^{1}H NMR (270 MHz) and ^{13}C NMR spectra were obtained on a JEOL JNM-GSX270 Fourier-transform NMR system. Unless otherwise specified all NMR spectra were obtained in deuterated chloroform using tetramethylsilane as an internal standard. Routine mass spectra were obtained on a Hewlett-Packard 5988A gas-liquid chromatography mass spectrometer system.

2.1.2 Preparation of mercaptomethyl p-tolyl sulfone 3. The preparation and properties of the mercaptosulfone **3** have been described earlier [4].

2.1.3 Preparation of p-tolyl 2-hydroxyethyl sulfide 6. Sodium metal (3.7 g, 0.161 mol) was added to a cooled volume of methanol (200 mL). Thiocresol (10.1 g, 0.081 mol) was added. A solution of chloroethanol (6.5 g, 0.081 mol) was added dropwise over 30 min. The ice/water bath was removed and the reaction mixture stirred at ambient temperature for 24 hours. Water (250 mL) was added and the resultant mixture washed with chloroform (five 100 mL aliquots). The combined organic layers were dried ($MgSO_4$), filtered and the solvent

evaporated. The residue was rectified at reduced pressure affording sulfide alcohol **6** (11.6 g, bp 100–138 °C/1.5 torr). Distilled **6** was chromatographed on silica gel (1.35 kg) employing 1:1 petroleum ether/chloroform (twenty two 200 mL fractions) followed by chloroform (200 mL fraction) for elution. Fractions 58-89 were combined and concentrated and the residue distilled at reduced pressure affording clean sulfide alcohol **6** (9.8 g, 0.058 mol, 72%, bp 128 °C/1.3 torr, lit. 155 °C/20 torr [18, 19]). **6** had IR 3367 cm^{-1}. ^1H NMR (270 MHz) δ 2.31 (s, 4H, CH_3/OH), 3.04 (t, $J = 6$ Hz, 2H), 3.69 (t, $J = 6$ Hz, 2H), 7.10 (d, $J = 8.1$ Hz, 2H), 7.29 (d, $J = 8.1$ Hz, 2H). ^{13}C NMR δ 21.0, 38.0, 60.2, 129.9, 130.9, 131.1, 137.0. MS: 168 (91%, $M^{+\cdot}$), 137 (100%), 91 (47%).

2.1.4 Preparation of p-tolyl 2-chloroethyl sulfide 7. Thionyl chloride (7.0 g, 0.06 mol) was dissolved in dry chloroform (100 mL) and the reaction mixture refluxed. The sulfide alcohol **6** (9.8 g, 0.06 mol) was dissolved in dry chloroform (50 mL) and the resultant solution added to the reaction mixture dropwise (addition time, 40 min). Upon completion of the addition, the reaction mixture was refluxed for 3 h. The solvent was evaporated and residue rectified at reduced pressure (10.1 g, 0.054 mol, 90%, bp 108–110 °C/1.5 torr, lit. 125–129 °C/6 torr [18, 19]). IR showed no OH absorption. **7** had ^1H NMR (270 MHz) δ 2.32 (s, 3H), 3.15 (t, $J = 7.8$ Hz, 2H), 3.57 (t, $J = 7.8$ Hz, 2H), 7.13 (d, $J = 7.8$ Hz, 2H), 7.31 (d, $J = 7.8$ Hz, 2H). ^{13}C NMR δ 21.1, 36.9, 42.4, 130.0, 130.4, 131.4, 137.5. MS 188 (27%), 186 (68%, $M^{+\cdot}$), 137 (100%).

2.1.5 Preparation of p-tolyl 2-thioacetoxyethyl sulfide 8. Thiolacetic acid (5.0 g, 0.066 mol) was added to dry pyridine (100 mL). The chloroethyl sulfide **7** (10.1 g, 0.054 mol) was added and the reaction mixture immersed in a constant temperature bath (80 °C) for 48 h. Chloroform (300 mL) was added to the reaction mixture and the resultant solution extracted with 5% v/v hydrochloric acid (seven 100 mL portions). The organic layer was dried ($MgSO_4$), filtered and the solvent evaporated. The residue was rectified at reduced pressure affording unchanged chloroethyl sulfide **7** (4.1 g, 40%) and the thiocetoxyethyl sulfide **8** (4.8 g, 0.021 mol, 32%, bp 160–170 °C/2 torr). **8** had IR 1691 cm^{-1}. ^1H NMR (270 MHz) δ 2.31 (s, 6H, SAc/ArCH_3), 3.02 (s, 4H, SCH_2CH_2S), 7.10 (d, $J = 8.1$ Hz, 2H), 7.30 (d, $J = 8.1$ Hz, 2H). ^{13}C NMR δ 21.1, 29.0, 30.6, 34.1, 129.9, 130.7, 131.1, 136.8, 195.3 MS 226 (17%, $M^{+\cdot}$), 150 (100%), 124 (38%), 91 (43%).

2.1.6 Preparation of p-tolyl 2-thioacetoxyethyl sulfone 9. *p*-Tolyl ω-thiocetoxyethyl sulfide **8** (4.8 g, 0.021 mol) was added to a mixture of potassium chromate (4.3 g, 0.022 mol) in glacial acetic acid (500 mL) and the reaction mixture refluxed for 30 min [20]. Chloroform (2 L) was added and the resultant mixture washed with 10% w/v sodium hydroxide (four 1 L aliquots). The organic layer was dried ($MgSO_4$) and the solvent evaporated affording crude sulfoxide thioacetate. Crude sulfoxide thioacetate was dissolved in acetone (375 mL). Anhydrous magnesium sulfate (24.4 g) and acetone (175 mL) were added and the mixture stirred at ambient temperature. Potassium permanganate (3.1 g, 0.020 mol) was added in three separate portions and work-up initiated after ninety minutes. Crude reaction mixture was filtered through celite and the solvent evaporated. The sulfone thioacetate **9** was chromatographed on silica gel (480 g) employing chloroform (100 mL fractions) for elution. Fractions 23–42 were combined and concentrated affording clean sulfone thioacetate **9** (3.96 g, 0.015 mol, 73%). A portion of the sulfone was recrystallized from methanol (m.p. 61–63 °C, lit. 64.5–66.0 °C [21]). $C_{11}H_{14}O_3S_2$ requires C, 51.1; H, 5.5. Found: C, 51.4; H, 5.4. **9** had IR 1679, 1317, 1147 cm^{-1}. ^1H NMR (270 MHz) δ 2.26 (s, 3H), 2.43 (s, 3H), 3.10 (m, 2H), 3.28 (m, 2H), 7.34 (d, $J = 7.8$ Hz, 2H), 7.76 (d, $J = 7.8$ Hz, 2H). ^{13}C NMR δ 21.7, 22.2, 30.4,

55.6, 128.2, 130.1, 135.6, 145.2, 194.6. MS 157 (29%), 151 (70%), 139 (41%), 91 (60%), 43 (100%).

2.1.7 Preparation p-tolyl 2-mercaptoethyl sulfone 4. The sulfone thioacetate **9** (1.6 g, 6.1 mol) was dissolved in a mixture of water (30 mL) and THF (120 mL). Concentrated sulfuric acid (1.2 mL) was added and the reaction mixture refluxed for four days. Chloroform (300 mL) was added to the reaction mixture and the resultant solution extracted with 2.5% w/v sodium hydroxide (three 150 mL portions). The combined aqueous layers were acidified with concentrated hydrochloric acid (25 mL) and the resultant solution washed with chloroform (five 300 mL portions). Those five chloroform layers were combined, dried ($MgSO_4$) and filtered. The chloroform was evaporated affording crude **4**. A duplicate run was carried out and the crude product combined with that of the first run providing a total of 0.671 g of **4**. The combined crude was chromatographed on silica gel (67 g) employing 1:1 petroleum ether/chloroform (70 mL) for elution. Fractions 27–31 were combined and concentrated furnishing **4** (0.44 g, 2.0 mmol, 33%). Chromatographed mercaptosulfone **4** was recrystallized from methanol (1 mL) at ambient temperature giving clean mercaptosulfone **4** (0.35 g, mp 73.2–74 °C). **4** had IR 2566, 1313, 1137 cm^{-1}. ^1H NMR (270 MHz) δ 1.64 (t, $J = 8.4$ Hz, 1H), 2.80 (m, 2H), 3.33 (m, 2H), 7.38 (d, $J = 7.6$ Hz, 2H), 7.76 (d, $J = 7.6$ Hz, 2H). ^{13}C NMR δ 17.4, 21.7, 59.8, 128.2, 130.1, 135.7, 145.2. MS 157 (58%), 151 (65%), 139 (34%), 92 (69%), 91 (100%), 61 (99%).

2.1.8 Preparation of p-tolyl 3-bromopropyl sulfide 10. Sodium metal (1.8 g, 0.079 mol) was dissolved in methanol (100 mL). p-Tolyl mercaptan (10.0 g, 0.080 mol) was added and the reaction mixture cooled with an ice/water bath.

1,3-Dibromopropane (16.3 g, 0.080 mol) in methanol (50 mL) was added dropwise over 0.5 h. The cooled reaction mixture was stirred for 1.5 h. Water (125 mL) was added and the resultant mixture extracted with chloroform (three 100 mL aliquots). The combined organic layers were dried ($MgSO_4$), filtered and the solvent evaporated. Crude residue was chromatographed on silica gel (400 g) employing petroleum ether (seventy 100 mL fractions) followed by 1:9 chloroform/petroleum ether (100 mL fractions). Fractions 76–100 were combined and concentrated. The residue was rectified at reduced pressure affording clean bromosulfide **10** (2.0 g, 0.008 mol, 10%, bp. 132–133 °C/1.1 torr, lit. 106 °C/0.3 torr [22]). **10** had ^1H NMR (270) δ 2.10 (quin., 2H), 2.31 (s, 3H), 3.01 (t, $J = 7.0$ Hz, 2H), 3.51 (t, $J = 6.8$ Hz, 2H), 7.11 (d, $J = 6.8$ Hz, 2H), 7.25 (d, $J = 8.1$ Hz, 2H). ^{13}C NMR δ 21.1, 31.9, 32.0, 32.8, 129.8, 130.6, 131.8, 136.6. MS 246 (53%), 244 (50%, $M^{+\cdot}$), 137 (100%), 91 (43%).

2.1.9 Preparation of p-tolyl 3-bromopropyl sulfone 11. The bromosulfide **10** (1.5 g, 6.2 mmol) was dissolved in chloroform (50 mL) and the resultant solution cooled with an ice/water bath. m-Chloroperoxybenzoic acid (50%, 4.7 g) was added in small portions over 1 hour. The reaction mixture was stirred at ambient temperature for 7 days. Chloroform (100 mL) was added and the resultant mixture washed with 2.5% w/v sodium hydroxide solution (two 100 mL portions). The organic layer was dried ($MgSO_4$), filtered and the solvent evaporated. Crude bromosulfone was recrystallized from methanol affording clean **11** (1.4 g, 5.1 mmol, 82%, mp 76.9–77.4 °C, lit. 74–75 °C [22]). **11** had IR 1311, 1137 cm^{-1}. ^1H NMR (270 MHz) δ 2.26 (quin., 2H), 2.44 (s, 3H), 3.22 (t, $J = 7.6$ Hz, 2H), 3.47 (t, $J = 6.2$ Hz, 2H), 7.35 (d, $J = 8.1$ Hz, 2H) 7.76 (d, $J = 8.1$ Hz, 2H). ^{13}C NMR δ 21.7, 26.0, 30.8, 54.8, 128.1, 130.1, 136.0, 145.0. MS 278 (6%), 276 (6%, $M^{+\cdot}$), 155 (39%), 131 (100%), 91 (92%).

2.1.10 Preparation of p-tolyl 3-thioacetoxypropyl sulfone 12. The bromosulfone **11** (1.0 g, 3.6 mmol) and thiolacetic acid (3.7 mmol) were added to dry pyridine (25 mL) and the reaction mixture stirred at ambient temperature for seven days. Chloroform (150 mL) was added and the resultant mixture extracted with 2.5% v/v hydrochloric acid (200 mL aliquots) until the aqueous pH remained acidic. The organic layer was dried ($MgSO_4$), filtered and the solvent evaporated. Crude thioacetate was chromatographed on silica gel (100 g) employing chloroform (100 mL fractions) for elution. Fractions 8–11 were combined and concentrated affording clean sulfone thioacetate **12** (0.335 g, 1.2 mmol, 33%). **12** had IR 1691, 1315, 1145 cm^{-1}. ^1H NMR (270 MHz) δ 1.98 (quin., 2H), 2.29 (s, 3H), 2.45 (s, 3H), 2.94 (t, $J = 7.0$ Hz, 2H), 3.14 (t, 7.6 Hz, 2H), 7.36 (d, $J = 7.8$ Hz, 2H), 7.76 (d, $J = 7.8$ Hz, 2H). ^{13}C NMR δ 21.6, 23.3, 27.3, 30.6, 54.9, 128.0, 130.0, 135.9, 144.8, 195.0. MS 272 (13% $M^{+\cdot}$), 166 (53%), 157 (84%), 91 (65%), 43 (100%).

2.1.11 Preparation of p-tolyl 3-mercaptopropyl sulfone 5. The thioacetoxysulfone **12** (0.335 g, 1.23 mmol) and p-toluenesulfonic acid (0.128 g) were added to a solution of ethylene glycol (2.5 mL) in benzene (30 mL). The reaction flask was equipped with a Dean-Stark trap and the reaction mixture refluxed for four days. Chloroform (100 mL) was added and the resultant mixture extracted with water (three 100 mL aliquots). The organic layer was dried ($MgSO_4$), filtered and the solvent evaporated. The residue was chromatographed on silica gel (33 g) employing 2:1 chloroform/ petroleum ether (30 mL fractions) for elution. Fractions 31–34 were combined, concentrated and recrystallized from methanol affording clean mercaptosulfone **5** (0.063 g, 0.27 mmol, 22%, mp 41.2–42.8 °C). $C_{10}H_{14}O_2S_2$ requires C, 52.1; H, 6.1. Found: C, 51.8; H, 6.3. **10** had IR 2568, 1315, 1147 cm^{-1}. ^1H NMR (270 MHz) δ 1.32 (t, $J = 8.3$ Hz, 1H), 2.00 (quin., 2H), 2.44 (s, 3H), 2.61 (d of t, 2H), 3.20 (t, $J = 7.6$ Hz, 2H), 7.34 (d, $J = 7.8$ Hz, 2H), 7.75 (d, $J = 7.8$ Hz, 2H). ^{13}C NMR δ 21.7, 23.2, 27.0, 54.6, 128.1, 130.0, 136.2, 144.9. MS 166 (100%), 157 (86%), 139 (51%), 91 (93%).

2.2 *Crystallography*

2.2.1 Preparation and crystal growth. Compound **3** crystallized (methanol) as small (mean dimension to 0.25 mm) euhedral crystals. Compound **4** crystallized (methanol) as small acicular crystals (0.03 mm thick and up to 1.00 mm long) elongated parallel to the *c* crystal axis. Compound **5** crystallized (methanol) as moderately large (mean dimension to 0.5 mm) anhedral crystals (figure 1).

2.2.2 Experimental data and refinement. From each of the families of crystals described above, a well-formed single crystal was selected and trimmed to an appropriate size. In the case of compounds **3** and **5**, the resulting crystal fragments were attached to nylon loops using Paratone oil. In the case of compound **4**, a small fragment was attached to a glass fiber using nail polish. In each case, the resulting assembly was mounted on a Bruker-AXS Proteum diffractometer. Data collection was performed at 23(2) °C (compound **4**), or 100(2) K (compounds **3** and **5**). All attempts to freeze crystals of compound **4** to 100 K were unsuccessful, resulting in fragmented crystals.

For each crystal, highly-redundant area-detector data were collected using monochromated copper radiation ($\lambda = 1.54178$Å) to a maximum resolution of approximately 0.8 Å. The resulting frames were integrated and final cell parameters calculated using SAINT [23]. SADABS [24] was used to apply an absorption correction, to which a spherical component was added. Crystal data and refinement parameters for **3–5** are summarized in table 1.

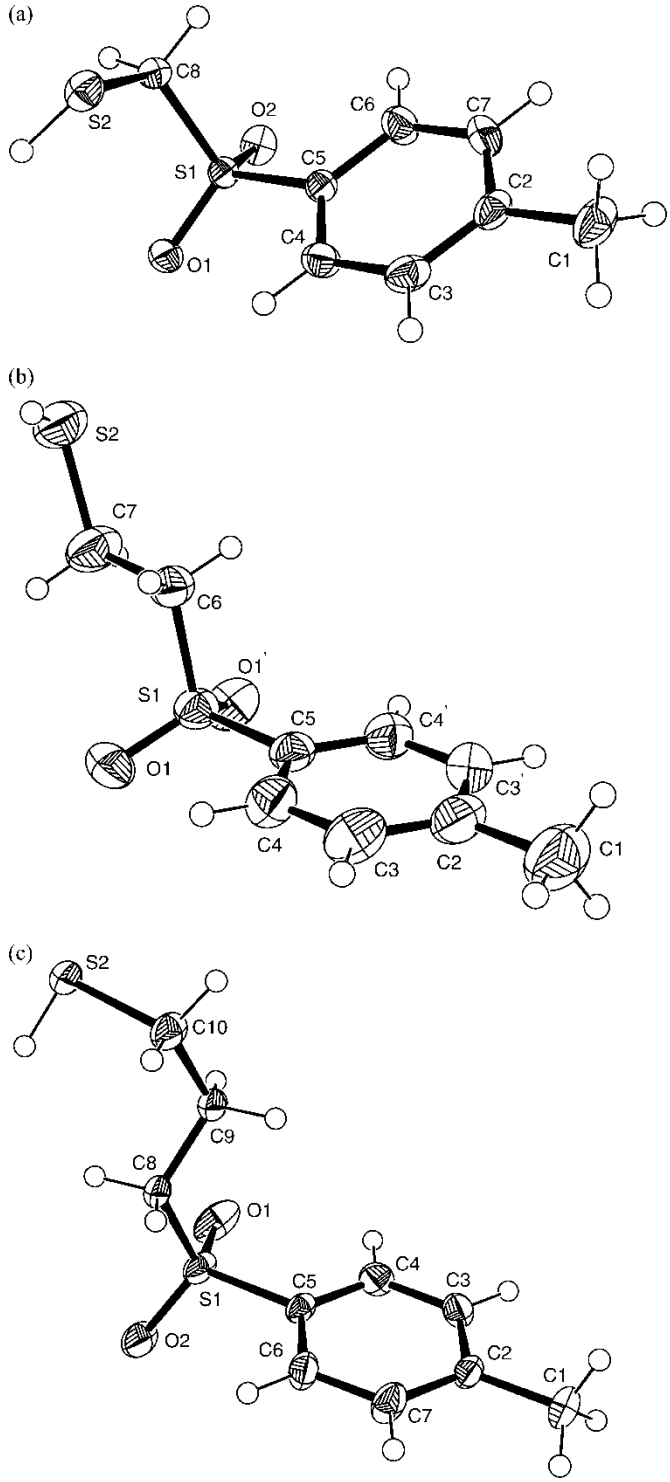


Figure 1. ORTEP3 [27] rendering of molecular structure, ADP ellipsoids at 50% probability, H spheres of arbitrary radius; a) compound **3**; b) compound **4**; c) compound **5**. Note that the representations of the methyl group and mercapto H of compound **4** are simplified (see text).

Table 1. Crystal data and refinement parameters.

	3	**4**	**5**
Formula:	$C_8H_{10}O_2S_2$	$C_9H_{12}O_2S_2$	$C_{10}H_{14}O_2S_2$
Formula weight:	202.28	216.31	230.33
Crystal system:	Triclinic	Orthorhombic	Triclinic
Space group:	$P\bar{1}$ (IT #2)	Pnma (IT #62)	$P\bar{1}$ (IT #2)
Crystal colour:	Colourless	Colourless	Colourless
Crystal dimensions (mm):	0.20 × 0.16 × 0.10	0.17 × 0.05 × 0.03	0.14 × 0.12 × 0.11
Unit cell parameters			
a (Å):	6.8771(3)	24.3370(12)	5.2380(2)
b (Å):	7.4811(3)	8.8107(5)	9.2954(3)
c (Å):	9.9826(4)	4.8518(3)	12.0241(4)
α (°):	93.074(2)	90	106.270(1)
β (°):	106.564(1)	90	95.983(1)
γ (°):	107.255(1)	90	95.431(1)
Z:	2	4	2
μ (mm^{-1}):	4.85	4.37	4.13
Transmission factor range:	0.44–0.63	0.52–0.88	0.54–0.63
2θ range(°):	9.34–137.74	7.26–138.44	7.74–137.56
Reflections measured:	9970	16259	10861
Independent reflections[†]:	1646	1029	1972
Refined parameters:	117	78	137
R_{int}:	0.041	0.043	0.039
R_σ:	0.026	0.015	0.021
S (GooF):	1.05	1.11	1.08
R1 (# refs)[‡]:	0.034 (1609)	0.033 (930)	0.043 (1897)
wR2[§]:	0.093	0.100	0.114

[†]All independent reflections were used in refinement.
[‡]R1 based on reflections for which $F_o > 4\sigma(F_o)$, the number of which is noted.
[§]wR2 is the refined parameter, and includes all reflections.

The resulting sets of reflections were processed to determine the space group; direct methods were used to determine an initial structure. In each case, all non-H atoms were observable in the initial map. Structure refinement proceeded easily using SHELXL [25]. Anisotropic ADPs were applied to the non-H atoms. H atoms (excepting the mercapto H) were added to the structure using a riding positional model (see reference [25] for details) and the isotropic ADPs of chemically-similar hydrogen atoms constrained to be equal. Examination of the residual electron density map revealed the location of the mercapto H; this atom was allowed to refine freely. The atomic disorder identified in the structure of **4** (see section 3.2 below) was modeled as a superposition of ideally-disordered sites with half occupancy for the methyl group and the mercapto hydrogen.

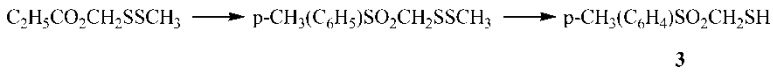
All further information, including the final atomic positions, has been submitted to the CSD under deposition numbers 286056, 286057 and 286058.

3. Results and discussion

3.1 *Organic synthesis*

3.1.1 Compound 3. The preparation of **3** was accomplished in two steps (see scheme 1) from a disulfide propionate [4]. Access to the starting material was provided by permanganate oxidation of dimethyl disulfide in propionic acid solution [20]. Deprotection of the

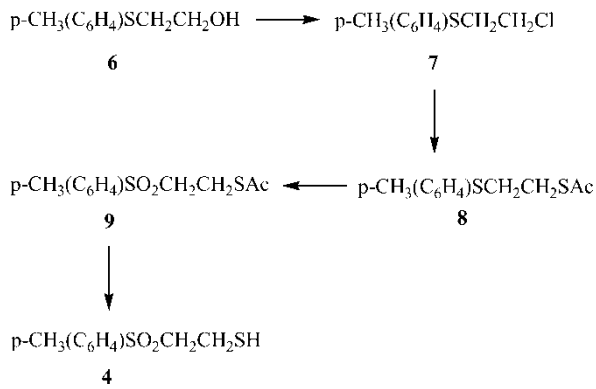
α-sulfone disulfide, as shown in scheme 1, is a delicate step which was carried out by means of benzenethiol in methylene chloride employing a catalytic amount of pyridine [2, 4].



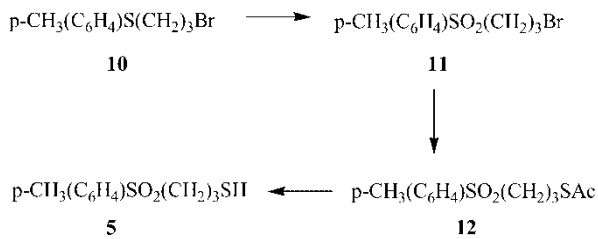
SCHEME 1

3.1.2 Compound 4. Condensation of p-tolylmercaptan and chloroethanol afforded **6**. Standard functional group transformations afforded the 2-thioacetoxy sulfone **9** (see scheme 2). Deprotection of **9** was carried out in refluxing aqueous THF employing acid catalysis. Acid catalysis was selected to avoid complications which might arise with base catalysis *e.g.* elimination of thioacetic acid followed by Michael addition of an intermediate sulfone mercaptide anion to give, *inter alia*, di-p-toluenesulfonylethyl sulfide.

3.1.3 Compound 5. The synthesis of **5** (see scheme 3) employed reagents and conditions similar to those utilized for the synthesis of **4** (see scheme 2) with the exception of the final step. The thioacetate **9** (scheme 2) was deprotected by acid-catalyzed hydrolysis, whereas the thioacetate **12** was deprotected by acid-catalyzed transesterification using ethylene glycol in benzene. Hydrolysis gave a somewhat better yield.



SCHEME 2



SCHEME 3

3.2 *Crystallography*

3.2.1 Compound 3. Crystals of this molecule are triclinic, space group $P\bar{1}$ (IT #2), with a single molecule in the asymmetric unit. The six carbon atoms comprising the phenyl ring show no significant deviation from flatness, however C(1) and S(1) are significantly (0.014(3) Å and 0.028(3) Å, respectively) out of that plane.

The phenyl rings of the two inversion-related molecules are strictly parallel to each other, but their centers are somewhat offset along a vector roughly normal to the molecular axis. The molecules are so arranged in the unit cell that the aromatic "heads" and the mercapto "tails" are segregated into alternate layers (figure 2a), these layers being parallel to the (001) crystallographic plane. Contrary to the hypothesis mentioned in the introduction, examination of the structure reveals no significant opportunities for intramolecular hydrogen bonding in the crystal. In particular, there are no hydrogen bonds of any kind involving the mercapto hydrogen H1S; this lack of constraint leads to moderate positional disorder of this atom, reflected in a relatively large isotropic ADP. The relatively large ($U_{eq} = 0.0396(6)$ e$^-$/Å^3) and distorted ($U_{max}/U_{min} = 3.4$) C1 displacement ellipsoid also reflects a moderate amount of positional disorder.

3.2.2 Compound 4. Crystals of this molecule are orthorhombic, space group Pnma (IT #62). The molecular axis, including C(1), C(2), C(5), C(6), C(7), S(1) and S(2), lies on the mirror plane, thus restricting the geometry of the molecule and reducing the number of molecules in the unit cell to four. The six carbon atoms comprising the phenyl ring show no significant deviation from flatness, however the methyl carbon (C5) is moderately (0.023(7) Å) and S1 significantly (0.072(5) Å) out of that plane. The presence of a mirror plane through the C(1) methyl group requires either that the group be disordered about the C(1)-C(2) axis, or that one hydrogen lie in the mirror plane. The current data support a model of disorder. Similarly, examination of the observed electron density near the mercapto S reveals that H1S is not located in the mirror plane, but is disordered into two equivalent sites on either side of that plane.

The crystal packing of molecules is seen to consist of columns of molecules (figure 2b) running along the [001] direction; in these columns, the molecules are "spoon packed". The molecules are so arranged in the unit cell that the aromatic "heads" and mercapto "tails" are segregated into alternate layers, these layers being parallel to the (100) crystallographic plane. The only significant possibility for hydrogen bonding is found between neighboring columns of molecules. This bond, between the mercapto H and an oxygen in the neighboring column, has a length of 2.50 Å and an approximate strength of 0.05 v.u. [26]. The H1S position, however, appears to represent a single hydrogen ideally disordered (either statically or dynamically) over two sites, and thus only four (one per molecule) of the possible eight hydrogen bonds per unit cell can actually be formed at any time.

That the ADPs for this molecule are generally significantly larger than those seen in the two related structures is due in part to the higher temperature at which the structural data were collected. The observation that cooling the crystals (however slowly) to 100 K results in fragmentation of the crystal lattice suggests that an ordering of H1S or the terminal methyl group (or both) may occur at temperatures somewhat below 20 °C with a reduction in crystal symmetry. The enlarged ADPs may indicate atomic disorder related to an incipient stage in this transition.

Bearing this in mind, the C1, C7 and S2 ADPs are notable. For each of these atoms, the ADP is large ($U_{eq} = 0.0831(10)$, 0.0682(8) and 0.0663(3) e$^-$/Å^3, respectively) and relatively distorted ($U_{max}/U_{min} = 2.536$, 2.749 and 2.230, respectively), again indicating a significant

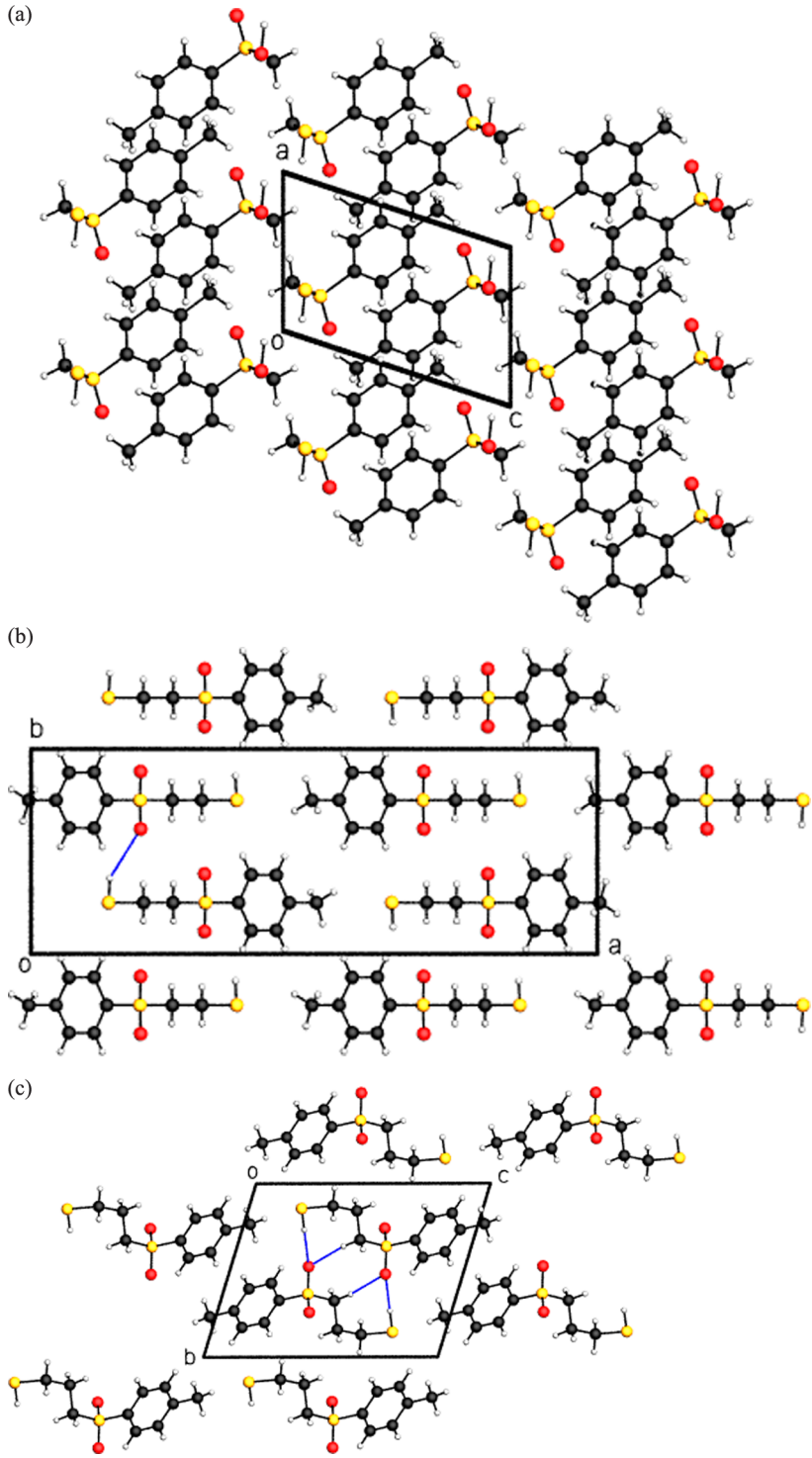


Figure 2. Rendering of molecular structure using spheres of arbitrary radius. Colors: C, black; O, red; S, yellow; H, gray. Unit cell outline and bonds are indicated in black, with representative hydrogen bonds indicated in blue. a) compound **3**, projection nearly along the *b* axis; b) compound **4**, projection along *c* axis; c) compound **5**, projection along *a* axis. Note that the representations of the methyl group and mercapto H of compound **4** are simplified (see text). Images generated using DRAWXTL [28] and POV-Ray [29].

amount of positional disorder. For all atoms lying in the mirror plane (with the exception of S2), U_{max} is normal to that plane, indicating that the primary axis of disorder is perpendicular to the plane. This is consistent with an ordering transition which would lower symmetry through loss of that mirror plane.

3.2.3 Compound 5. Crystals of this molecule are triclinic, space group $P\bar{1}$ (IT #2). The six carbon atoms comprising the phenyl ring show no significant deviation from flatness, however the methyl carbon C(1) is modestly (0.013(4) Å) and S(1) is significantly (0.034(3) Å) out of that plane.

The phenyl rings of the two inversion-related molecules are strictly parallel to each other, but (unlike the case of **3**), their centers are significantly offset, so that there is little overlap between adjacent rings. The molecules are so arranged in the unit cell (figure 2c) that the aromatic "heads" and the mercapto "tails" are segregated into alternate layers, these layers being parallel to the (010) crystallographic plane. There are two significant hydrogen bonding possibilities. The first forms between the mercapto H1S and O2 of an inversion-related molecule (2.40 Å), and the second between H8A and O2 of the same inversion-related molecule (2.39 Å), each with an approximate strength of 0.06 v.u. [26]; these have the result of forming hydrogen-bonded molecular dimers in the crystal structure. The ADPs of several atoms are striking for their anisotropy; O2, O1, S1 and C7 have U_{max}/U_{min} of 6.053, 5.036, 3.846 and 3.202, respectively. These values suggest that a significant amount of positional disorder remains in crystal structure at 100 K. Regrettably, the data are insufficient to resolve any particular model of disorder.

3.2.4 Comparison of crystal structures. Examination of the three crystal structures considered here reveals some interesting comparisons. As mentioned above, in all three structures the molecules pack so as to segregate the aromatic "heads" and aliphatic "tails" into alternating layers. Focusing on the quasi-two-dimensional sheets occupied by the molecular heads, we see that in the structure of **3**, each ring has six neighbors in approximate hexagonal coordination. Of those six, two are related by simple translation along the *a* axis while the other four are related by inversion. This arrangement is also seen in the structure of **4**; here translation is along the *c* axis. Unlike in the case of **3**, however, rings related by inversion are strongly offset, with the terminal methyl groups taking an important part of the packing. The structure of **5** also shows the six-fold coordination in the sheet of aromatic heads, with two neighboring molecules related by translation (along the *c* axis) and the remaining four by inversion. The packing of the aromatic heads resembles that of **4**, in that the terminal methyl groups appears to take an important part. In all three structures, it appears that a modest energy reduction may be accomplished by stacking of aromatic rings, although in no case is the stacking very precise.

Focusing in turn on the layers formed by the aliphatic tails, the most salient feature is that whereas in the structures of **4** and **5**, the tails extending from opposite sides of the sheet interdigitate completely, in the structure of **3** they are folded in such a way as to minimize the interdigitation. As can be seen in figures 2a–c, this folding precludes opportunities for the hydrogen bonding seen in **4** and **5**.

The calculated crystalline densities of **3**, **4**, and **5** are 1.446, 1.381 and 1.380 g/cm^3, respectively. Given the similarity of the molecules, it is clear that the packing of **3** is significantly more efficient (i.e. incorporating less void space) that that of **5** (comparison with **4** is problematic, as this structure was collected at significantly higher temperature). This difference is particularly striking inasmuch as molecule **3** is relatively rigid, having fewer torsional degrees

of freedom than **4** and **5**, and so might be expected to be more awkward to pack. It is possible that the reduction in crystalline enthalpy reduction caused by the formation of hydrogen bonds in **5** (and perhaps also in **4**) is sufficient to offset the essentially entropic effect of decreased packing efficiency.

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